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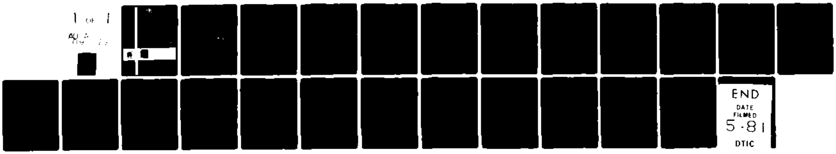

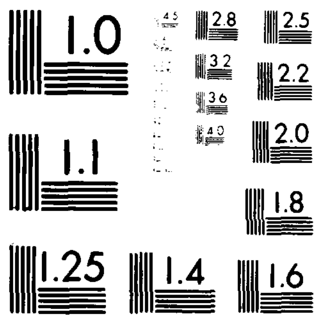

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(6) DIGITAL COMMUNICATIONS SYSTEMS:
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VOLUME I. SUMMARY.

Prepared for

U. S. Army Electronic Proving Ground
Fort Huachuca, Arizona

(12) 24

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TUCSON, ARIZONA

Final Report

DIGITAL COMMUNICATIONS SYSTEMS: TEST AND EVALUATION STUDIES
VOLUME I: SUMMARY

Contract No. DAEA18-74-A0271/0005

Prepared for

U. S. Army Electronic Proving Ground
Fort Huachuca, Arizona

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1.0 INTRODUCTION

This is the final report to be prepared for the Material Test Division, Instrumentation and Methodology Branch, of the U. S. Army Electronic Proving Ground, Fort Huachuca, Arizona, under Contract DAEA18-74-A-0271/0004 and 0005. The purpose of the contract was to undertake a program of applied research to provide comprehensive standards and test methodologies, including recommended instrumentation, data collection, data reduction, and analysis criteria for digital communications systems and equipment. The primary objective was to identify meaningful, measurable parameters, recommend instrumentation required to obtain these measurements, and to provide analysis methodologies and performance criteria.

The scope of the overall study was focused on those measurable parameters that are purely digital in nature or relate directly to the digital error performance of the equipment or system being examined.

The purpose of this portion of the final report is to provide a brief summary of the previous reports arranged according to specific areas of interest. The general categories are Digital Communications Theory, Evaluation of System Performance, Instrumentation and Methodologies, Reduction of Test Time, and A New Technique for Equipment Alignment. Each area within these general categories is referenced to the specific sections in the earlier reports where complete detailed information can be obtained.

The sections which make up the specific areas under each category are in general spread throughout the total series of reports. However, the reports can be broadly identified in three chronological groups.

The first four reports [1-4] were quite general and tutorial in nature. They provide an excellent starting point for those engineers and technicians who are not familiar with digital communications techniques, as well as a clear and concise review and summary for those who have been involved previously with these aspects.

The primary purpose of the next series of five reports [5-9] was to extend the general studies to make more specific recommendations on evaluation criteria, instrumentation, and methodologies. The TRI-TAC family of digital group multiplexers was selected as a vehicle for study which would produce some immediately useful results.

The final series of five reports [10-14] was devoted primarily to the validation of the extrapolation technique for the evaluation of digital communications equipment. It was found that curves of long term bit error rate versus signal-to-noise ratio could be useful results of bench testing of digital communications equipment. Present methods for obtaining complete data for such curves are very time-consuming. The extrapolation technique can reduce this test time by up to three to four orders of magnitude.

2.0 DIGITAL COMMUNICATIONS THEORY

2.1 General

Here as throughout, the specific areas of interest range from very elementary subjects which are presented in tutorial form, to some rather complex derivations for the probability of bit error for specific modulation techniques and detection methods. Hopefully the coverage is sufficiently broad that an interested person can determine an entry point in order to obtain the information he desires.

2.2 Methods of Bit Error Analysis

This discussion, which is contained in Section 2 of the April 1977 report [2], began with some precise definitions of various bit error patterns, and with the definition and derivation of some statistics of interest. A block diagram representation of a typical data communications system was presented and the concept of the error sequence was introduced. Bit error rate (BER) was discussed in detail with emphasis on the fact that BER is a random variable and is difficult to measure precisely.

Since BER measurements of themselves lack much of the detail necessary to accurately determine system performance, the ideas of block error rate and throughput were discussed and compared with BER as figures of merit. It was illustrated that the usual independent error assumption is not valid in most cases and that throughput calculations based on long term BER yield a worst case estimate of the actual throughput.

Bursts, gaps and intervals were defined and discussed in relation to the performance of real channels. Some other statistics were presented as often being of interest with regard to performance analysis of digital systems.

The next subsection related typical error rates and patterns to the modulation scheme used in implementing the digital channel. Since burst error patterns are due predominantly to external channel phenomena, it was noted that BER is of prime interest in relation to modulation. Other than in the case of double errors in comparison detection there are no distinguishable error patterns that can be attributed directly to the modulation scheme.

2.3 Typical Performance of Real Channels

This consisted of a very general discussion of the performance of real channels (Section 3 of the April 1977 report [2]), which was broken down into the areas of modulation techniques and transmission media.

The comparison of modulation schemes was judged on their performance in additive Gaussian noise. It was pointed out that most impulse noise and burst phenomena can be attributed to external channel anomalies and that if digital modulation systems are ordered by relative performance in the presence of Gaussian noise, this ordering will also be valid for impulse noise and many other disturbances. It was further pointed out that at least the first order effects of internal error causes (with the possible exception of intersymbol interference) can be approximated by a fixed decrease in the effective signal to

Gaussian noise ratio. These facts are quite important, and form the justification for much of the work subsequently performed on the contract.

A very general discussion was presented of baseband modulation systems in relation to bandwidth utilization, intersymbol interference, and signal-to-noise ratio necessary to maintain a given BER. The more common methods of carrier modulation, frequency shift keying and phase shift keying, were discussed presenting the general relationships among the coherent, non-coherent and M-ary variations.

Four basic transmission media were then examined: the telephone channel, line of sight UHF and SHF radio, tropospheric scatter and HF radio. These media were found to have very distinctive characteristics. The telephone channel is typified by short error bursts of high density interspersed in longer periods of relatively low error density. Line of site microwave has typically very low noise level but is subject to rapid, frequency selective, multipath fading that normally must be overcome by diversity operation. Troposcatter systems are subject to slow fading, which is frequency independent, as well as to multipath fading. It is this slow fading that causes the slowly varying error densities typical of tropospheric scatter. High frequency radio is highly susceptible to atmospheric and man-made noise as well as slow fading. Error patterns resemble those of the telephone line but the bursts are of longer duration with less density and the average error rate is typically higher. In all cases the bursty nature of the channels and relatively unpredictable nature of their characteristics imply that BER alone is not an adequate statistic on which to base performance criteria.

2.4 Theoretical Probability of Error and Calculated BER Curves

Derivations of expressions for probability of bit error for various modulation schemes and methods of detection, and calculations of the effects of internal receiver anomalies on the characteristic curves of bit error rate (BER) versus signal-to-noise ratio were accomplished in an effort to establish the validity of the extrapolation technique for shortening the test time necessary to obtain these characteristic curves for specific items of equipment (see Section 5.1 of this report).

The basic hypothesis to be proved was that small variations in the internal anomalies which contribute to errors in digital demodulators cause a lateral displacement of the characteristic curve of bit error rate versus received signal-to-noise ratio while the curve retains its theoretical shape at the higher levels of signal-to-noise ratio. The objective was to verify the hypothesis both mathematically and experimentally to the extent possible for a variety of modulation schemes.

The initial derivations and calculations were spread throughout the January, March, and May reports of 1979 [11-13]; however, the results have been consolidated and expanded in Chapters 2, 3 and 5 of Volume II of this report. The following chapter references pertain to that document.

In Chapter 2 expressions are derived for the probability of error for ideal detection of signals in additive white Gaussian noise for the most common methods of modulation. These ideal theoretical

expressions are then modified to determine the effects of carrier phase reference error and symbol synchronization error. Since closed form expressions cannot be determined for the effects of intersymbol interference and receiver nonlinearities, the theoretical aspects of these anomalies are discussed in Chapter 3 as calculated results.

In Chapter 3 the derived expressions are also used to calculate and plot BER curves to examine the effects of the various factors on their position and shape. In those cases where closed form expressions were not attainable, the anomalies are studied directly in terms of how they affect the BER curves.

The first section of Chapter 5 is devoted to correcting an apparent disparity between the calculated effects of jitter and experimentally obtained BER curves. Contents of the remainder of Volume II are summarized elsewhere in this report.

3.0 EVALUATION OF SYSTEM PERFORMANCE

3.1 General

Again the discussions range from the very general to the specific. Existing standards for performance criteria were examined and a survey was made of those criteria presently in use. These criteria were applied to the testing and evaluation of a typical digital communications system. Some specific recommendations were made for performance criteria to be applied in evaluating the TRI-TAC family of digital group multiplexers (DGM).

3.2 Existing Standards for Performance Criteria

In Section 4 of the April 1977 report [2] an examination was made of existing standards for performance criteria, and it was found that very few exist. Extensive efforts in this direction are presently being made by the FCC, NBS, DCA as manager of the NCS, and the Office of Telecommunications of the Department of Commerce, however. The intent is to provide standard definitions of performance criteria for digital communications systems from the point of view of the user that are also tractable to the commercial communications carrier. These efforts were briefly reviewed.

3.3 A Survey of Performance Criteria

Also in Section 5 of the April 1977 report [2] a survey was made of the performance criteria that have been used by various agencies in testing and evaluating digital equipment and systems. The most common statistic used for evaluation is a plot of BER

versus signal to Gaussian noise ratio. Similar plots are used to determine the effects of both co-channel and adjacent channel interference. Other criteria include availability, throughput, and various burst and gap statistics.

3.4 Testing and Evaluating an Example Digital Communications System

In Section 6 of the April 1977 report [2] some test statistics were proposed as being applicable to several different categories of testing. The suggested categories were: production acceptance type testing, developmental testing, and experimental testing. The test statistics that would probably be of most interest in each category were listed.

Section 2 of the June 1977 report [4] described a proposed general model of a digital communications system test. This included discussion of a test configuration, the statistics recommended for performance evaluation, and the instrumentation recommended for measuring and recording raw data.

3.5 User Channel Performance Testing and Evaluation

Performance testing and evaluation of user channels as derived by the TRI-TAC family of digital group multiplexers were discussed in Section 3 of the January 1978 report [6] in relation to what parameters are necessary to determine the degree to which the experiment meets specific performance requirements. This was further analyzed in terms of data formats and calculation of statistics that are possible with reasonable modification of available test instrumentation (see Section 4.3 of this report).

3.6 Multiplexed Channel Testing and Evaluation

In Section 4 of the January 1978 report [6] a method was discussed for obtaining availability data on high data rate multiplexed channels. This evaluation method was related to a second mode of operation of test instrumentation (see Section 4.8 of this report) and formulated into a detailed statement of requirements.

3.7 Recommendations on Tests of a Family of Digital Group Multiplexers

The entire report of March 1978 [7] was devoted to recording the results of an in-depth review of the design of the family of digital group multiplexers to determine what parameters and special test procedures will be necessary to obtain adequate data to determine performance relative to specified criteria. That report focuses primarily on the bench testing of the DGM family and provided some specific comments based on a review of the design plans and detailed test plans.

The May 1978 report [8] completed the review of the tests of the DGM family by providing specific comments on the System Test Plan. Emphasis was placed on the interoperability tests. Comments were directed primarily to the interactions of the DGM's during loss of synchronization in various links. This work was continued in Section 2 of the July 1978 report [9], where some suggested configurations were proposed for system tests of those TRI-TAC assemblages that contain, as components, items from the family of digital group multiplexers.

One of the tests required in the evaluation of the DGM's is to determine compliance with the specification for frame synchronization maintenance. Direct testing could require thousands of hours to complete. Section 2 of the March 1979 report [12] was devoted to an examination of the shortened tests performed by the contractor and to the recommendation of alternative test methods.

4.0 INSTRUMENTATION AND METHODOLOGIES

4.1 General

Considerable time was devoted to the investigation and discussion of instrumentation and methodologies for the conduct of equipment and system tests. These ranged from general discussions of desired data to specific descriptions of test sets and their employment. Most of the more specific work was directed toward the test and evaluation of the TRI-TAC DGM's.

4.2 Measurement and Recording of the Error Sequence

Section 2 of the May 1977 report [3] began with a discussion of instrumentation and recording techniques for the measurement of the bit error pattern and computation of the statistics of interest. This was followed by a short discussion of methods of recording the error sequence. It was concluded that by using source encoding techniques it is possible to record error sequences with relatively inexpensive hardware at transmission rates as high as several Mbps. Even higher rates can be accommodated by use of more expensive equipment. It was further noted that most meaningful error patterns are at rates of 100 Kbps or less. Some suggestions for computation of statistics were also given.

4.3 Data Collection and the Use of the Safeguard Equipment

Section 2 of the November 1977 report [5] began to discuss an approach to digital error pattern collection and analysis and the

possible use of the Digital Acquisition Interface Units (DAIU's) and the Digital Channel Performance Evaluators (DCPE's), which were available from the SAFEGUARD program. It was concluded that the DAIU's would not be particularly useful, but that the DCPE's could, with modification, form the nucleus of the digital test configuration for the TRI-TAC program and could be made sufficiently flexible to have general application to future digital testing.

4.4 Phase Jitter and Its Measurement

Section 3 of the November 1977 report [5] was devoted to an analysis of phase jitter, its causes, effects, and some possible techniques and instrumentation for its measurement.

4.5 Functional Description and Recommended Configuration of the DCPE

Section 2 of the January 1978 report [6] described in detail the operation and existing capabilities of the DCPE's. In Section 5 the parameters that were determined as necessary for the operational evaluation of user channels and multiplexed channels of the TRI-TAC family of DGM's were translated into detailed statements of requirements for the modification of the DCPE's.

5.0 REDUCTION OF TEST TIME

5.1 General

One of the early tasks of the contract was to examine alternative methods for the reduction of test time, particularly as it pertained to obtaining data for the plotting of curves of long term BER versus signal-to-noise ratio. Several methods were examined as are briefly described in the following paragraphs. Since the extrapolation technique was found to have considerable promise, the majority of the last five reports was devoted to the validation of the technique both experimentally and theoretically. This material is of considerable importance, and has been collected and extensively presented in Volume II of this report.

5.2 Extrapolation

The discussion of extrapolation as a method of reducing test time in obtaining low level BER and curves of BER versus RSL or S/N was begun in Section 4 of the May 1977 report [3]. From our previous report we had concluded that on real channels long term BER was not particularly useful, and that other statistics determined from error patterns were necessary. Curves of long term BER are significant primarily in production acceptance testing or other bench testing of hardware. We had determined that for the most part the first order effects of error causes internal to equipment can be approximated by a fixed decrease in the effective signal to Gaussian noise ratio.

Therefore we postulated that BER curves plotted from data taken under controlled conditions should closely follow a theoretical curve based upon the modulation scheme employed, but shifted laterally an amount fixed by the equipment quality. This hypothesis was substantiated by the use of several examples. It was then suggested that a sufficiently accurate measurement of equipment performance can be obtained by fitting a theoretical curve through a single point at a moderate (10^{-4}) BER. Points of much lower BER (10^{-7}) obtained from this curve would be approximately as accurate as points determined by counting errors in normal test procedures. Thus test time for obtaining BER curves can be shortened by four to five orders magnitude.

As was mentioned above the September and November 1978 reports [10,11] and the January, March, and May 1979 reports [12,13,14] were almost entirely devoted to establishing the validity of the extrapolation technique. The theoretical portions were described in Section 2.4 of this report. The experimental results are described in considerable detail in the December 1978 and January 1979 reports and are further analyzed in Chapter 4 of Volume II of this report.

Specifically, the experimental work was conducted in an attempt to verify the hypothesis that small variations in the internal anomalies which contribute to errors in digital demodulators cause a lateral displacement of the characteristic curve of bit error rate versus received signal-to-noise ratio, while the curve retains its theoretical shape at the higher levels of signal-to-noise ratio. Experiments were conducted on available digital communications systems which encompassed

three different methods of modulation. Where feasible, perturbations of error causes were introduced into the systems to determine their effect upon the BER curves. Chapter 5 of Volume II of this report contains comparisons of the experimental results with theoretically calculated predictions.

5.3 Sequential Testing

Section 3 of the May 1977 report [3] examined the technique of sequential testing and presented several examples to illustrate possible applications of the technique to the determination of BER. It was concluded that, in those situations where hypothesis testing is appropriate, sequential procedures can reduce average test times by as much as 50%. It should be emphasized that in many situations, such as production or preproduction acceptance testing, hypothesis testing is really more appropriate than parameter estimation and is much easier to accomplish.

5.4 Estimation of BER Using Extreme Value Theory

An interesting but highly theoretical method for estimating very low bit error rates was examined in Section 3 of the June 1977 report [4]. The complexity of the computations necessary to produce an estimate were found to be not justified by the relatively small saving of test time that could be realized.

6.0 A New Technique for Equipment Alignment

During the course of the experimental work described in Section 5.2 above the patterns of the error curves suggested a new procedure for the alignment of digital communications equipment that could have a far greater significance than the reduction of test time. This procedure, which is based upon the validity of the extrapolation technique, is described in some detail in the December 1978 report [11] and in Chapter 4 of Volume II of this report. The conclusion was that analog techniques for alignment of digital communications equipment are well established and necessary to obtain proper operation. However, these methods may not produce the best possible operational performance. Final alignment while monitoring the bit error rate can produce the desired *optimum performance*. This contention is very strongly supported by the experimental results.

7.0 BIBLIOGRAPHIES

The first report on this contract (March 1977 [1]) was an "Annotated Bibliography on Test and Evaluation of Digital Communications Systems and Equipment." It was the result of a survey of current literature describing recent advancements in digital communications theory and technology. The purpose was to establish a ready reference to those articles and reports which pertain directly or are closely related to test and evaluation of digital communications systems and equipment. Those articles considered most pertinent were annotated in the second section of the bibliography. There are 239 references listed of which 43 are annotated.

The survey focused on articles and reports published during the five-year period 1972 through 1976. References from prior years were included in those cases where they were found to be particularly pertinent or where they were deemed necessary as a basis for understanding more recent articles. Many of these references, as well as many additional ones, are discussed and interpreted in context in all subsequent reports. A complete consolidation and further annotation of all the references cited in the series of reports would be a first task in the continuation of this effort.

8.0 CONCLUSION

As was stated in the INTRODUCTION, the primary objective of the applied research under this contract has been to identify meaningful, measurable parameters, recommend instrumentation to obtain these measurements, and to provide analysis methodologies and performance criteria. This objective has been attained, as described in the above summary, and has resulted in several important new techniques.

Potentially the most significant result is the recommended technique for optimum alignment of equipment. The validation of the extrapolation technique for obtaining BER curves is also quite significant in reducing test time. The functional design of the DCPE will certainly fill a void in real channel testing capabilities. Although most of the other results are tutorial in nature they do provide a contribution toward the overall objective to all who may derive benefit from the information contained therein.

The true worth of the effort is much more difficult to estimate, however. This depends on how well the information has been accepted and assimilated by those persons directly involved in the testing and evaluation of digital communications equipment. Although the authors were in direct contact with only a limited number of these people, the interest, understanding, and acceptance of the material by this group was highly encouraging. It is hoped that the sequence of reports will be widely disseminated.

The authors are truly grateful for the assistance and courtesy provided to them by all persons who have been involved in the administration of this contract.

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